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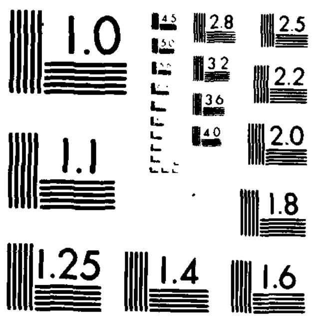

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STEVENS INSTITUTE OF TECHNOLOGY

CASTLE POINT STATION
HOBOKEN, NEW JERSEY

OVERVIEW
NASA/AF/NAVY SYMPOSIUM
ON
AEROELASTICITY OF TURBINE ENGINES

ME-RT-81003

F. Sisto

March 1981

~~AN~~ OVERVIEW

NASA/AF/NAVY SYMPOSIUM ON AEROELASTICITY

OF TURBINE ENGINES

at

NASA Lewis Laboratory, Cleveland, Ohio

October 27, 28, & 29, 1980

TECHNICAL REPORT ME-RT-81003

by

F. Sisto

March 1981

Prepared for

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STEVENS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING

Background and Introduction

The Office of Naval Research jointly with the Naval Air Systems Command had planned a Colloquium on Turbine Engine Aeroelasticity for April 24 and 25, 1980. The purpose of the meeting was to report on the present state of knowledge in this area as perceived by research contractors to the government. This was to be followed by a round table discussion of the participants to enhance coordination and to synthesize recommendations for the sponsorship of future work.

Simultaneously NASA Lewis in the Fluid Mechanics and Acoustics Division, jointly with the Materials and Structures Division had been planning a similar activity with a somewhat broader scope, particularly to include aerodynamic forcing and structural dynamics. Finally, a joint meeting was decided upon with additional participation by the Air Force and Air Force contractors.

The Symposium on Aeroelasticity of Turbine Engines was held on October 27, 28 and 29, 1980 at the NASA Lewis Laboratory with the participation as just described. The prime purpose as noted above was for the benefit of the government: to assist in the formulation of future research programs and justify the request for funds to be expended for that research. Clearly a second important benefit was to be the dissemination of up-to-the minute results amongst the research community in this important area of airbreathing propulsion systems.

The program of the Symposium appears as Appendix A.

Scope of the Symposium

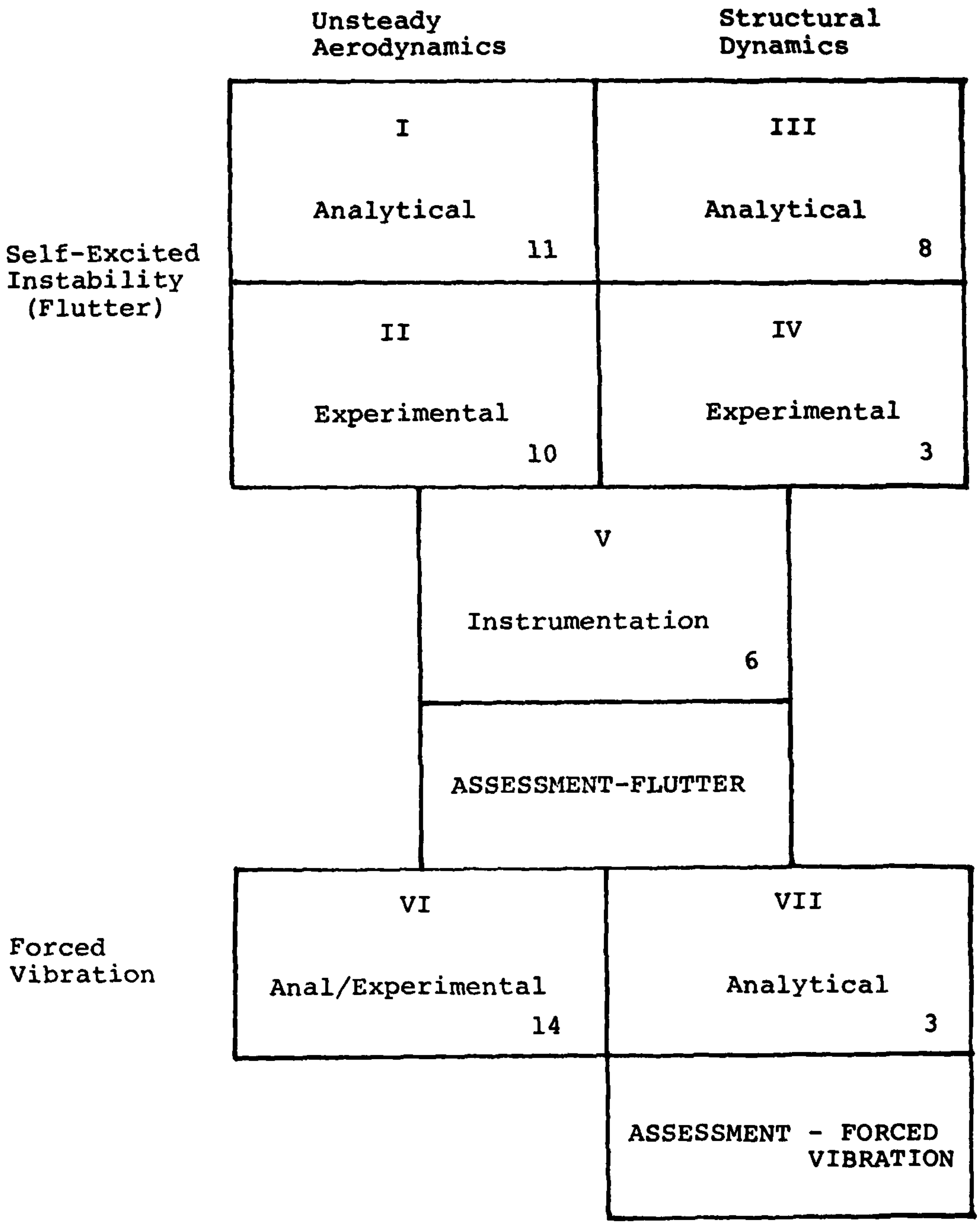
After formal welcoming ceremonies and programmatic reviews by government officials the meeting opened with a brief historical review of the subject. "A History of Aeroelasticity in Gas Turbine Engines in the United States and United Kingdom" appears as Appendix B to this Overview; it is not referred to again other than to note that the proceedings of the Symposium as it subsequently evolved seemed to fit smoothly and logically into the historical development of the subject.

Government programs in the 1970s decade which were of an antecedent or related nature were described by Melvin Hartmann for NASA and the Air Force and by James Patton for the Navy. With a number of precursor assessment meetings and preliminary research efforts, the Lewis/AFAPL cooperative program of 1975 led to the ATE (Aeroelastics of Turbine Engines) of 1976; the ONR/Navair programs had given issue similarly to a number of specific research tasks through Project Squid and 6.1 funding sources. Richard Bankhead amplified some of Hartmann's remarks drawing particular attention to a number of important emergent problem areas and concluding by noting that stress mapping of preproduction engines (and the aeroelastic implications of such efforts) would be a firm requirement of future engine acceptance procedures. Professor Max Platzer added to Patton's remarks particularly with regard to Navair and NPS programs.

The most significant antecedent meetings with closely related objectives were discussed by these speakers and a listing taken from a viewgraph supplied by Professor Platzer is shown below.

- 1972 AEROELASTICITY IN TURBOMACHINES
  DETROIT-DIESEL ALLISON - INDIANAPOLIS
- 1974 UNSTEADY FLOWS IN JET ENGINES
  UARL-HARTFORD
- 1975 UNSTEADY PHENOMENA IN TURBOMACHINERY
  AGARD-PEP, MONTEREY, CA.
- 1976 AEROELASTIC STABILITY OF FAN/COMPRESSOR BLADING
  AF/NASA/NAVY MEETING, DAYTON
- 1976 AEROELASTICITY IN TURBOMACHINES
  IUTAM-PARIS
- 1977 UNSTEADY AERODYNAMICS
  AGARD-FDP, OTTAWA
- 1980 AEROELASTICITY IN TURBOMACHINES
  IUTAM - LAUSANNE

In the following technical sessions major topical coverage was organized according to three categorizations: i) Self-Excited (Flutter) or Forced Vibration, ii) Analytical or Experimental, and iii) Unsteady Aerodynamics or Structural Dynamics. However, slightly more emphasis was given to Flutter than Forcing and more attention was devoted to Analysis as compared to Experimentation. In this program organization an important session on Instrumentation was devoted to a number of aeroelastic data acquisition and data processing systems, all considered here to be under the broader heading of experimental work.



In addition to the formal sessions a brief informal period was devoted to proposed compendiums by NASA (Advanced) and an AGARD group (Basic) on Turbomachine Aeroelasticity; two other brief assessment periods were devoted to summarization; very pertinent after dinner remarks were delivered on the night of the Symposium banquet by Professor Robert Loewy (See Appendix C) and a brief government meeting was held after the formal conclusion of the Symposium proper.

The sequel of this overview consists of brief summaries of the seven technical sessions and two assessment periods and concludes with an overall assessment of the present state of knowledge and recommended actions, including research. Abstracts and outlines of each presentation, appear in the separate proceedings document distributed at the Symposium.

The Technical Sessions on Flutter

I. The first technical session, comprised of eleven separate presentations, concentrated on the analytical aspects of unsteady aerodynamics related to flutter.

The presentations by Goldstein (1)*, Platzer and Adamson (2), Adamczyk (3), Verdon and Caspar (4), Caspar and Verdon (5), Adamczyk (9) in summary displayed considerable present capability to analyze two dimensional unsteady flow in cascades at high Mach numbers. Numerical evaluations of unsteady coefficients may now be obtained which include a number of effects of considerable importance to ensure the fidelity of the model being analyzed. These include shocks (moving and stationary, normal and oblique, weak and strong as appropriate), blade thickness and camber, mean flow deflection.

It seems that major controlling parameters are in the aggregate being taken into account, or at least being considered actively in ongoing research. Although some comparisons amongst the predictions of the several analytical treatments have been made, the results to some extent are inconclusive. Qualitative agreements, where comparisons are possible, seem to be good, but quantitative agreements are difficult to judge. Small discrepancies while not significant in themselves need to be explained, nonetheless, to increase confidence in the results being compared.

The remainder of the first technical session was devoted to low speed, stall flutter (2 presentations), choke flutter and analysis applied to an engine compressor: Atassi (6), Jeffers (7),

*Numbers refer to the presentation number assigned in the Program, Appendix A.

Sisto (8), Micklow and Jeffers (11) and Jeffers (10).

With exception of (6) this group of presentations lean more heavily on experiments and unconfirmed mechanisms for the explanations of flutter or for the "calibration" of semi-empirical theories. The intractability to analysis of stalling and choking unfortunately appears to be still a fact of life. Paper (6) shows the possibility of classical (i.e. coupled) flutter of low speed turbine blades at typical operating conditions; experimental confirmation of the validity of this conclusion should be anticipated by the R & D community.

II. The second technical session of ten presentations dealing with experimental aspects of flutter consisted of: three linear cascade studies by Riffel (12), Boldman (13) and Carta (14); an annular cascade presentation, by Jutras (15); five papers on flutter in rotors by Stargardter (16), Jutras (17), Crawley (18), Lubomski (19) and Kurkov (20); and a paper misplaced from Session VII relating experiment and design implications of forced vibration in blading by Oldakowski (21).

The linear cascade results were valuable in being most directly applicable to confirmation, as in (12), of analytical results, typical of those presentated in Session I, which are two-dimensional aerodynamic theories without exception (rotors are modelled by cascades at one representative radius). These experiments also serve to guide those analyses, by discovery of anomolous phenomena such as shock wave location in (13) and by confirming cascade periodicity of pressure response (14).

The annular cascade (15), approaching engine geometry more nearly, provided data that could perhaps be applied stripwise to an actual three dimensional rotor cascade with greater validity than data from a linear cascade.

The rotating cascade studies were characterized by the maximum validity, or fidelity, for the engine design and operation application. By the same token the data acquisition and data processing are much more difficult and structural dynamics aspects unavoidably become involved. As the full capability of modern instrumentation and spectral analysis are applied some very exciting and worthwhile insights are being drawn into unsteady aerodynamics as it must actually appear in the engine. Although the most expensive in terms of capital and operating costs, these programs are the most valuable in achieving the goals of experimentation; confirmation and guidance of analysis. Naturally, they also have intrinsic value for mapping the time-varying parameters of actual engine operations.

III. The third technical session of eight presentations in analytical structural dynamics related to flutter consisted of three papers on bladed-disc flutter by Kielb (22), Srinavasan (23) and Smith (24), a group of related studies in a single presentation by Johnson (25) and four papers related to various aspects of damping: Drake (26), Soni (27), Srinavasan (28) and Sridhar (29).

The lead presentation (22) essentially described the planned in-house NASA program in analytical structural dynamics and dealt with mistuning for the first time from the analytical viewpoint. Session I had not recognized this important effect, although the linear aerodynamic theories could presumably accommodate to this description of the structural dynamics. And papers (19) and (20) in Session II had recognized mistuning as an observable fact in experimental programs with bladed-disc assemblies.

Since mistuning and the complication of the system mode by blade-disc interactions is a structural dynamics effect, it was not unexpected to see this topic developed at some length in the subsequent papers in this session. Capability and understanding seem greatly advanced; a residual effort seems to be needed to accommodate certain nonlinear effects and the numerical handling of very large systems.

The group of four papers on damping emphasized the very important part played by this parameter in the aeroelastic behavior of practical systems. The analysis of anticipated mechanical damping levels from various sources as well as the avenues for intentional enhancement of damping by design seem to be well understood in general. Specific applications will benefit from the insights drawn from these papers.

IV. The fourth technical session on the experimental aspects of structural dynamics consisted of three presentations by Morris (30), Cutts (31) and Stange (32). In actuality (31) dealing with damping measurements was incorporated into (28) of the previous session and (32) was moved to Session VII.

In particular the presentations of the NASA spin rig facility (30) with strain gage and fiber optic sensors and the AFAPL rotating rig (32) using derotated holographic interferometry both described exploratory programs for elucidating the behavior of mistuned bladed-disk assemblies undergoing forced vibration synthesized of travelling waves in the disk and for the measurement of damping.

In total, these Session IV papers described the very useful and sophisticated rigs and equipment now available for measuring all aspects of the modal description of vibrating rotor blades and discs. Without such apparatus and the output of experimental data the comparable analytical programs would lose a great deal of validity.

V. The fifth technical session on instrumentation consisted of six presentations in which structural measurements were dominant. The first two presentations devoted to aerodynamics measurements by England (33) and Shreeve (34) were followed by the four devoted to stress and vibrations: Nieberding (35), McCarty (36), Frarey (37) and Kiraly (38). These papers, as a group, showed the excellent and detailed measurement of dynamic quantities that may be obtained by coupling fairly simple and straightforward sensors to sophisticated and modern data processing systems. In particular, digitization and subsequent data manipulation on microprocessors and microcomputers was shown to be a very powerful technique in repeated instances.

Assessment of Flutter Status

The fifth technical session concluded the major portion of the program and was followed by an immediate assessment period in which a number of persons participated. Calvin Ball led the discussion by posing 5 questions, reproduced below, and then calling upon various participants to express themselves on any or all of the questions.

Some Issues Related
to Flutter

1. General status of flutter technology?
2. Continued studies of existing data/analyses?
3. Generic technology *vs*. design systems - distribution of effort?
4. "A unified flutter, forced vibration prediction systems" - what is required?
5. What areas appear important/feasible?

Passing immediately to the third question almost all participants including this reporter, were of the opinion that generic technology was the way to go. Analytical, and even experimental, programs should be configured in such a way that information concerning turbine engine aeroelasticity was generated in "modules" (the word was used by Michael Stallone, Sid Sattar called them building blocks). It was then up to the individual, the design team, the research teams, etc., to connect these modules into a loosely knit system for the purpose at hand: design, prediction of aeroelastic behavior of an engine, an experimental rig, etc. A number of different "design systems" could result.

In this context the remainder of the discussion is related to the subject area and state of information that might be contained in each module and not so much to the modular concept for connecting them into specific design systems.

By the same token, the answers to question number 4 were essentially negative. That is to say that a single unified flutter/forced vibration system is not an item of the highest priority. Given a menu of dependable modules (qualified by experimental means) to draw from, the user should have less trouble assembling them into a system.

Specific answers to the first question concerning the status of flutter technology were conflicting or else noncommital. However, the general consensus, obtained by integrating the totality of comments and weighing them in the light of this question is that the State of Flutter Technology is "Good".

Consequently the remainder of the assessment can be reported by dealing most closely with the remaining questions, 2 and 5: the need for continued studies of existing data and analyses and the areas that appear important and feasible.

·Sid Sattar (P&W, Conn.) wondered when design systems would become available; in the meantime he thought that better aerodynamics (e.g., the effects of loading, thickness and shocks) were needed and better structural capability (e.g., complicated and nonlinear shroud boundary conditions). These improved states of knowledge and the application of controlled mistuning might allow the very desirable elimination of rotor blade shrouds in the future. He cautioned that mistuning had to be done in a manner that did not create forced response problems (AR = 3.0). Subsequent to the Symposium a communication was received from

Pratt & Whitney over Sid Sattar's signature reiterating and expanding upon these comments. Additionally he felt that the nonsteady aerodynamics solutions would be numerically derived, that NASA should (industry would not) make a comparative evaluation of existing basic and advanced flutter analyses to calibrate sensitivity to operating conditions, and that mistuning theory should be applied to the interpretation of existing flutter rig results because these were by nature mistuned blade rows.

•Bob Jay (DDA) felt that an improvement in transonic flutter technology was vitally needed although no specific aerodynamic work was suggested. He expressed concern over the use of intentional mistuning and advocated a consideration of "random" mistuning. He thought that identification and additional work were needed on dampers and damping coatings, experimental verification of benefits, in particular using non-interference techniques of data acquisition for "real" stress and assessment of damping effectiveness.

•Mike Stallone (GE, Ohio) noted that a great deal of work had been done on analysis and experiment. He then made the previously noted remarks concerning modular systems. What was needed now was their correlation; i.e., verification that analysis predicts performance properly. He felt that instrumentation needed more attention, in particular to ensure reliability, but speculated that NASA would probably not spend more money on developing those instrumentation systems.

•Jim Caruthers (U. Tenn.) opined as an aerodynamicist that an adequate level of technology in unsteady high speed aerodynamics exists now and that the main decision to be made was on specifically how to apply mistuning analysis to alleviate blade flutter. He felt supersonic flutter at high back pressure was treated by Adamczyk's and Goldstein's analyses which covered an extensive range of governing parameters. Some additional work might also be required in the intermediate back pressure range where new analyses/codes had just been presented by them. A remaining need was for transonic stall flutter analysis and an experimental verification, indeed, that stalling of the airfoils was involved. If so the perturbation approach is inadequate and an inherently nonlinear treatment will be required. Anticipating results of the presentations in upcoming Session VI he noted that aerodynamic forcing still needed research because the flow was inherently rotational and a new series of analyses were needed for nonzero loading and/or thickness and/or camber.

•Vince Cardinale (GE, Mass.) was gratified to observe the mutual support of each other's work displayed by designers and researchers. He then noted some statistics describing modern compressor and fan stages and observed (again anticipating Sesssions VI and VII) that, with low aspect ratio blades low cycle fatigue was a problem related to second engine order excitation. He emphasized that flutter avoidance was often at odds with steady aerodynamic performance objectives and that flutter avoidance in three separate regimes (transonic stall, part speed choke in core compressors and supersonic shock) were themselves internally contradictory insofar as measures to be taken. Could this problem be solved, and if so, how?

He asked whether any one had actually tried detuning? (Ed. note: intentional <u>mis</u>tuning has often been considered a favorable procedure in flutter, but unfavorable in forced vibration; <u>de</u>tuning implies the change of <u>all</u> blade frequencies up or down to move a resonance up or down in physical rpm.) He also noted that specifying constant tolerance on airfoil contour resulted in relatively highly tuned blades in large sizes and mistuning in small blading.

•Mark Kulina (C-W), an attendee, subsequent to the Symposium, sent a letter to organizer Calvin Ball (NASA/LeRC), noting that K was granted patent 4,097,192 in June 1978 on intentional blade mistuning to control rotor blade resonant vibratory responses. Eight previous patents are cited with similar objectives. The extent to which any or all of these mistuning strategies have been put into practice in industry would be important to know. Furthermore, the "rogue blade" theory developed at Rolls Royce seems to be a contraindication for mistuning when it is done to avoid resonant stresses.

•Joe Verdon (UTRC) commenting only on aerodynamic theory noted that present NASA codes not yet used in industry include effects of supersonic shock and high back pressure, blade shape, and choking flow; solution of the transonic problem is just around the corner. He noted in all of this that the perturbation approach has yielded valuable information; he saw considerable development needed in the future using the full Euler equations and numerically treating rotational flow, large amplitude vibrations, periodic stalling, bubble collapse, viscous separation, strong shocks, etc.

•Dick Bankhead (AFAPL) noted that the Air Force intended to have design and design assessment capabilities and not have to rely on industry for this. This capability was needed for acceptance procedures and for monitoring performance of new systems. Mistuning was probably not a viable concept because it could not be maintained in the field with in-service engines; maintenance procedures were too complicated, etc.

•Mel Roberts (GE, Ohio) noted, as a nonaeroelastician, what he thought were contradictory statements he had heard concerning current capability to predict high supersonic flutter. Consequently he felt the answer to question number one which could lead to a comprehensive assessment of various aspects of the state-of-the-art in flutter technology was a very valuable possible outcome. At the base of this contradiction was the assumption that the steady state aerodynamics was well-known, but this is not clearly so. He went on to make a plea for approximate analyses that erred on the side of conservatism; more precise aerodynamic and structural computer codes were often nonlinear and too expensive to use. Some effort should be expended on the cost/benefit ratio of using particular codes. An iterative design and development sequence was suggested with approximate theory being used to predict the flutter performance and also guide the development fixes. He concluded with pleas for technology assessment in the area of friction and damping and for the coordinated evaluation and use of experimental data banks existing in the various companies.

•Max Platzer (NPS) drawing a parallel with aircraft experience asked for detailed unsteady aerodynamic measurements to validate the various aerodynamic theories despite some possibly fortuitous good agreements when flutter speeds were predicted and then measured. He continued to be puzzled by the apparently good flutter prediction obtained with flat plate theories.

•Hans Stargardter (P&W, Conn.) urged additional experimental work too, and in addition a more thorough evaluation of existing experimental data banks. Analytical procedures could be finally validated only be experiment; in particular the exact mechanism of so-called stall flutter needs to be discriminated experimentally. Is the mechanism due to the appearance of a shock or separation? Is the shock steady or oscillating?

The Technical Sessions on Forced Vibration

VI. The sixth technical session consisted of fourteen presentations dealing with analytical aspects of aerodynamically forced vibration (9 papers) and also reporting on aerodynamic forcing experiments (5 papers). Four analytical presentations by Atassi (39), Englert (40), Caruthers (41) and Williams & Dowell (42) comprise an introduction to unsteady rotational and vortical flows in stationary cascades.

The first is limited to incompressible flows, the second is for supersonic onset flow with in-passage shock, the remaining two are limited to two-dimensional compressible flow (and being small perturbation theories also treat airfoil motion). In the practical range of operating parameters the initial results do not seem to be substantially different from the flat plate, potential flow theories. However, the work must be considered introductory and further evaluation, along with more extensive parametric studies, are needed to assess their relative value for applications (design).

The next paper by Seidel (43) analyzes the attenuation of a distorted inflow by a single stage transonic compressor using semi-actuator disc theory. This practical and useful design tool bears only indirectly upon aerodynamically forced vibrations of blades. Similarly the next two papers by Linn (44) and Kurosaka (45) deal with unsteady flow and acoustic phenomena in ducts with impressed circumferential distortions or swirl. These efforts, while important in themselves, bear upon aeroelastic blade vibrations only through subsidiary or ancillary calculations that must be performed to arrive at unsteady blade loads.

In presentation (46) by Clem & Greitzer strut-induced flow nonuniformities are discussed along with an assessment of the unsteady rotor blade force resulting therefrom. The principal value of this work is in the prediction of flow perturbation amplitudes since the blade forces vary drastically depending on the validity of the lift (and moment) response model.

The paper by Caruthers & Kuroska (47) explores an important acoustic resonance problem in radial impellers resulting from diffuser vane excitations. The principal value of this exploratory analytical investigation is in lending credence to the hypothesized mechanism of this troublesome problem.

This concluded the analytical approaches in Session VI; the remaining five presentations by Okiishi (48), Jay & Bennet (49), O'Brien (50), Jay (51) and Williams (52) were reports on experimental programs.

The first of these presents a careful survey of the unsteady flow components attributable predominantly to blade wakes and occurring at a number of stations in an axial flow compressor. A qualitative agreement is claimed for the perturbation magnitudes and the hypothesized fluid mechanics mechanisms. In (49) somewhat similar upstream flow perturbations are measured simultaneously with the downstream stator vane surface pressures. Correlations between the spectra of these two signals lend greater insight into the unsteady blade response functions that must eventually be perfected.

In presentation (50) the force (integrated pressure) measurements are for a rotor blade rather than a stator vane as in (49) and a frequency-domain response function approach is taken to relate the force to the measured flow distortion. Paper (52) reports on the rotor blade first bending resonances with distortions found in typical VTOL inlets, obtaining rough correlation of stress level with the state of separation (distortion) in the inlet.

These response functions have been studied analytically in (39), (40), (41), and (42) and would be applied to the flow perturbations analyzed in (43), (44), (45), (46) and measured in (48), (49), (50) and (52).

The penultimate presentation (51) was a report on a linear cascade investigation of aerodynamic response to torsional vibration of turbine blade sections. This experimental research documented the need for analyses to treat highly loaded, thick, large turning airfoils with high solidity; it also tended to establish the inadequacy of quasi-static testing although the choice of zero interblade phase angle to do this was perhaps unfortunate.

VII. The final technical session consisted of only three papers, dealing exclusively with analytical topics in structural dynamics. The presentation by Jones & Muszynska (53) was an exhaustive investigation of damping in tuned and mistuned bladed disks. The results indicated important modifications of the maximum dynamic response amplitudes as a function of mistuning and of blade-to blade phase differences in the excitation forces.

The paper by Leissa (54) was an initial report on blade vibration analysis based on shell theory which is thought to be more valid than beam theory for very thin and/or low aspect ratio blades. The final presentation by Sisto & Chang (55) reported on initial studies of dynamic instability of cantilever rotor blades that may be expected when a turbine engine is subjected to high precessional rates as in rapid pull-up or yawing maneuvers of the aircraft.

At this juncture Professor Atassi gave a brief report on the recent meeting in Lausanne on Aeroelasticity in Turbomachines (see list on p. 3). The sponsor was the International Union of Theoretical and Applied Mechanics and the broad range of topics indicated ongoing international efforts on subjects similar to those being discussed at the present Symposium.

Assessment of Forced Vibration Status

This second assessment period of the Symposium immediately following the final technical session was chaired by Mel Hartmann. He posed a series of questions to stimulate comment and to help guide the discussion.

1. Flutter-forced vibration-relative need/status of technology
2. Status or need for emphasis, structural? aero aspects?
3. Detailed experimental data-available/type needed?
4. Development of generic technology vs. demonstration of suitability of technology?
5. What areas appear important/feasible?
6. Methods of technology transfer?

Again, the 4th question elicited a consensus that generic technology should be developed and perfected; the application of that technology in the design process could be left to industry. They would use it if it were just available at a reasonable cost. The theories and the computer codes developing the numerical solutions had to be expressed in such a way that they were economical to use.

With respect to the 2nd question no consensus could be established. Aerodynamicists and structural dynamicists each tended to express needs relative to their own areas of expertise, without prejudice to the possible needs of the others. Hence, other than eliciting valuable specific comments in specific instances, the relative need of emphasis between structural and aerodynamic aspects could not be established from respondents' comments.

The 6th question relating to methods of technology transfer generated some suggestions; the responses to the remaining questions (1, 3 and 5) are described below.

·Ed Greitzer (MIT) expressed a more general set of perceived needs for work in unsteady aerodynamics: the effects on steady state performance, on flows near the casing, on heat transfer, on rotating stall inception. Returning to the forced vibration case he noted, in referring to previous presentations, that wakes were not necessarily two-dimensional and that vorticity and acoustic disturbances were not uncoupled. Furthermore the multistage compressor still needed to be addressed with the expected stage interactions.

In a letter received by Cal Ball after the Symposium Ed noted that the question of how to predict the magnitude of the disturbance, or gust strength, in an actual compressor or turbine had not been addressed. He also drew attention to the need for work to define the vibratory amplitude in forced vibration, where linear superposition may not be valid for large disturbances.

·Lee Matsch (AirResearch) spoke exclusively about radial flow turbomachines, noting the predominance of forced vibration problems and the reliance on material damping, to the exclusion of coulomb damping, to resolve their problems. Hence he was able to recommend an emphasis on forced vibration and on structural aspects. He argued for the need for work on artificial damping (coatings, damper rings) and non-contacting strain measurements for small engines.

·Bob Jay (DDA) corroborated the pre-eminence of forced vibration problems in small engines and the resurgence of 2nd engine order resonance with the trend to lower aspect ratios. On the other hand he had more confidence in structural techniques and saw the need for work in the aerodynamics side (gust definition in a variety of regimes in compressors and turbines, aerodynamic damping, economizing numerical aerodynamics codes, acquisition of experimental data). He felt that a semi-annual aeroelastic newsletter (in addition to symposia) would enhance technology transfer beneficially.

•Shinu Srinavasan (UTRC) noted that improved analysis and controlled testing in the areas of aerodynamic excitation, resonance and damping would have to be conducted in order to achieve the objective of a shroudless blade and to counter expected problems with the trend to low aspect ratios. Material damping data had to be improved in quantity and quality and put on a consistent basis of use to the designer. He characterized the Symposium as a "conference on mistuning". Frequency checking as a prerequisite to installing blades probably cannot be recommended at this time; rather a statistical approach is required such as he had outlined. He thought technology transfer would not be a problem since no one would intentionally ignore knowledge developed in university, government and industry research programs.

•Jack Henderson (AFWAL) noted the successful applications of a viscoelasticity damped inlet guide vane on the TF 30, on stators on the TF 41 and other nonrotating components in other engines. Believing that the state of the art was adequate, he invited the audience to propose to him a similar demonstration program for a fan rotor blade that he could subsequently advocate.

•Dave Jones (AFWAL) agreed with many of the points of the previous two speakers with respect to damping and wished to express his own point of view from the vantage point of the Air Force laboratories. With respect to mistuning, this was always present to some degree and hence understanding the phenomenon was important. As far as mechanical and material damping (linear and nonlinear) a great deal of work remained to be done. Midspan shrouds represent a limited viewpoint of what can be done. How was damping to be attained in integral blade systems (blisks) and low aspect ratio blades? What do we all do about it? His final pleas were for advocacy by industry to the government for what they specifically need and for the governmental groups to coordinate their activities.

•Bill Stange (AFWAL) noted very briefly that the propulsion laboratory as a whole was very interested in mistuning despite some previous comments that may have conveyed the opposite thought.

•Ted Woldakowski (GE, Ohio) commented on strain measurement techniques, particularly on small blades. He felt the light probes did not give meaningful results for small blades and/or higher modes where amplitudes of 50 mills or less are equivalent to the endurance limit of the material. Miniaturization of strain gages was recommended.

•Frank Carta (UTRC) emphasized that for both unsteady aerodynamics and structural dynamics what was sorely needed for a good design system was a series of "benchmark experiments" to calibrate the analyses; calibrating one analysis against another was unsatisfactory.

Summary

Summarization of the Symposium will be attempted in rather global terms and with the intent of recommending specific actions. Since these conclusions are recognized as being somewhat subjective and do not carry any official imprimatur, the act of summarization in this manner can do more good than harm.

Blade flutter research has received more attention and has resulted in a more mature technology than the field of aerodynamically forced vibration. The work has been supported directly and indirectly by the government and details of funding distribution among university, industry and government laboratories is available within the bureaucracy. Important and interesting work remains to be done in blade flutter, but the emphasis should now shift to forced vibration. Many topics which apply to both technologies (e.g., non-aerodynamic forms of damping) obviously should continue to receive attention with appropriate priority.

Unsteady blade aerodynamics for flutter application needs to have some parameter ranges filled in (e.g., intermediate back-pressure in the supersonic regime) and all existing analyses codified and put on a common basis. NASA Lewis is the obvious agency for coordinating this effort and subcontracting the needed additional work. Industry sources should be encouraged to review their unsteady aerodynamics codes and determine which should remain proprietary and which need not be proprietary. The latter should be submitted to NASA for codification. It is believed that this process will automatically select in favor of cost-effective computer codes. Dissemination policy could also be determined by NASA and then effectuated in a clearinghouse mode. A semiannual aeroelasticity newsletter should be considered.

Existing banks of experimental aerodynamic data should be handled in a similar manner with the additional objective of calibrating the analyses described above. Most importantly, however, the experiments should be screened for appropriateness in the calibration function (i.e., same underlying physical conditions and assumptions) and a select small number of new experiments should be designed specifically to prove or disprove the theory. Rather than use existing hardware exclusively, special apparatuses should also be designed to fulfill this function. (Outside of their aeroelastic value these new rigs need not represent good practice or modern geometry in relation to actual compressors or turbines).

Unsteady aerodynamics related to gust functions and forced excitation may require new analyses such as those introduced in Symposium Session VI. The characteristics of acoustic, rotational, vortical and entropic, 3-D disturbances may become important when these disturbances are strong, as they often may be.

Some thought should be given, however, to a more general aerodynamic treatment that handles both flow disturbances and blade vibration simultaneously since these perturbations are coupled one to another as well as to others (such as those perturbations associated with the proximity of adjacent blade rows).

The topic of mistuning should be subjected to a separate investigation by an aeroelastician, or an aeroelastic team. To subject mistuning to separate aerodynamic and structural dynamic analyses is to invite confusion and inadvertent obfuscation.

A mistuned bladed disc assembly should be subjected to an aeroelastic stability analysis, and also to an aerodynamic forcing analysis, using the most accurate aerodynamic and structural descriptions possible. Parametric studies of this system should then provide some presently missing insight into the benefits and dangers of mistuning, and perhaps generate a viable strategy for its use. Parts of this study are currently underway, but the scope of a single, unified study needs to be defined and then the study initiated (or consolidated from the existing parts).

Non-aerodynamic forms of damping (material, mechanical, coulomb, hysteretic, etc.) are important in blade aeroelasticity, but it is difficult to recommend a cohesive, well-organized program of research. An exception to this statement is a recommendations to draw together and put on a consistent basis the damping properties of different engineering materials, perhaps with confidence limits on the data. Damping projects of the sort that are currently underway should continue, but how to organize a new, integrated program on damping is a difficult task. Damping investigations would probably benefit from an increased orientation toward specific design applications and away from generalized concepts.

Instrumentation is clearly and beneficially moving toward simplified and non-invasive sensors coupled with high capacity, high-rate, data acquisition and spectral data processing systems. These program developments are well under way; extensions should be considered for measurement of quantities other than fluid pressure and blade deflection by non-interfering techniques. Measurement of unsteady fluid velocities and temperatures, actual blade material strains, etc., may be considered.

Unsteady flow has many interesting and important aspects that need research for better knowledge and definition. However, only those aspects of flow related to aeroelastic vibration are given attention here. Unsteady flow research in both flutter and forced vibration applications should begin to address the 3-D nature of the problem; the structural descriptions are already three dimensional and refinements (e.g., to include plate-type modes in the blading) should continue.

APPENDIX A

PROGRAM

JOINT
NASA/AF/NAVY

SYMPOSIUM ON
AEROELASTICITY OF TURBINE ENGINES

October 27, 1980

8:00 to 8:30 A.M.	Registration
8:30 to 8:45 A.M.	Welcome by Dr. S. Himmel, Associate Director, LeRC
8:45 to 9:30 A.M.	Overview - NASA Program, M. J. Hartmann - AF Program, M. Schmidt - NAVY Program, J. Patton/M. Platzer
9:30 to 10:00 A.M.	Introduction "History of Aeroelasticity in Gas Turbine Engines," by F. Sisto, Stevans Institute of Technology

Session I

10:00 to 12:40 P.M. 1:40 to 2:40 P.M.	Unsteady Aerodynamics - Flutter (Analytical) Chaired by M. Platzer, Naval Postgraduate School

- Unstalled Supersonic Flutter

Paper No. 1 "Unsteady Aerodynamics of Supersonic Operating Regime," by M. Goldstein, NASA/LeRC

2 "A Method of Characteristics Approach to Analyze Supersonic Blade Flutter," by M. Platzer, Naval Postgraduate School and T. C. Adamson, Jr., University of Michigan

- Stalled Supersonic Flutter

3 "Supersonic Stall Bending Flutter," J. Adamczyk, NASA/LeRC

- Subsonic/Transonic Stall Flutter

4 "Development of an Unsteady Cascade Analysis," by J. M. Verdon and J. R. Caspar, United Technologies Research Center

5 "Numerical Treatment of Unsteady Subsonic Flow Past an Oscillating Cascade," by J. R. Caspar and J. M. Verdon, United Technologies Research Center

- Subsonic/Transonic Stall Flutter (cont'd)

6 "Stability and Flutter Analysis of Turbine Blades at Low Speed," by H. Atassi, University of Notre Dame

7 "Evaluation of a Technique for Predicting of Stall Flutter in Turbine Engines," by J. Jeffers, A. May and W. J. Deskin, Pratt & Whitney Aircraft Group, Government Products Division

8 "Stall Flutter Research," by F. Sisto, Stevans Institute of Technology

LUNCH

9 "Transonic Flutter," by J. Adamczyk, NASA/LeRC

10 "F100 High Compressor Flutter Analysis," by J. Jeffers, M. R. Chi, D. A. Hilliard and G. Micklow, Pratt & Whitney Aircraft Group, Government Products Division

- Choke Flutter

11 "Semiactuator Disc Unsteady Aerodynamics Analysis for Choke Flutter Prediction," by J. Micklow, J. Jeffers and R. Sibley, Pratt and Whitney Aircraft Group, Government Products Division and H. G. Hurrell, NASA/LeRC

Session II

2:40 to 5:00 P.M. Unsteady Aerodynamics - Flutter (Experimental)
Cochaired by W. Stevans, NASA/LeRC and R. Bankhead, AF

- Cascade Experiments

12 "Experimental Determination of Unsteady Blade Aerodynamics in Cascade," by R. Riffel and M. D. Rothrock, Detroit Diesel Allison, Division of General Motors

13 "LeRC Transonic Oscillating Cascade Wind Tunnel," by D. R. Boldman and A. E. Buggele, NASA/LeRC

14 "Unsteady Cascade Periodicity," by F. O. Carta, United Technologies Research Center

- Cascade Experiments (cont'd)

15 "Experimental Analysis of Blade Instability," by R. Jutras, General Electric Company, Aircraft Engine Group

- Rotating Rig Experiments

16 "TS-22 Subsonic/Transonic Stall Flutter Program," by H. Stargardter, Pratt & Whitney Aircraft Group, Commerical Products Division

17 "A Program for Subsonic/Transonic Stall Flutter Study," by R. Jutras, General Electric Company, Aircraft Engine Group

18 "Measurements of Aerodynamic Damping in a Transonic Compressor," by E. Crawley, Massachusetts Institute of Technology

6:00 to 7:00 P.M. Cocktail Hour

7:00 to 8:30 P.M. Dinner

October 28, 1980

8:00 to 9:00 A.M. Unsteady Aerodynamics - Flutter (Experimental) Concluded

- Full-Scale Engine Experiments

19 "NASA Full-Scale Engine Aeroelasticity Programs," by J. F. Lubomski, NASA/LeRC

20 "Measurement of Aerodynamic Work During Fan Flutter," by A. P. Kurkov, NASA/LeRC

21 "Experimental Verification of Turbo Blading Aeromechanics," by T. Oldakowski, and V. Cardinale, General Electric Company, Aircraft Engine Group

Session III

9:00 to 11:40 A.M. Structural Dynamics - Flutter (Analytical) Chaired by G. Brown, NASA/LeRC

22 "Analytical Studies in Flutter and Forced Response of Bladed Discs," by R. Kielb and K. Kasa, NASA/LeRC

- Structural Dynamics - Flutter (Analytical) (cont'd)

23 "Effects of Mistuning on Fan Blade Flutter," by A. V. Srinivasen, United Technologies Research Center

24 "Bladed Disc Aeroelastic Analysis Code," by G. C. C. Smith, Bell Aerospace, Division of Textron, Inc.

25 "The Development of Models for Phenomena Identification Studies of Experimental Flutter Data," by S. Johnson, Lehigh University

26 "High Temperature Damping Applications to Increase Fatigue Life in Rotating Jet Engine Components," by M. L. Drake, University of Dayton Research Institute

27 "Finite Element Analysis of Viscoelastically Damped Rotating Structures-Free and Forced Vibration," by M. L. Soni and F. K. Bogner, University of Dayton Research Institute

28 "Blade Damping Mechanisms-An Overview," by A. V. Srinivasen, United Technologies Research Center

29 "Mechanical Damping in Jet Engine Blades-Mathematical Models," by S. Sridhar, United Technologies Research Center

Session IV

11:40 to 1:00 P.M. Structural Dynamics - Flutter (Experimental)
Chaired by J. C. McBain, AFWAL

30 "The Lewis Spin Rig Facility," by R. Morris, NASA/LeRC

31 "Measurement of Damping in Turbomachinery Blading," by D. Cutts, United Technologies Research Center

32 "Structural Dynamic Response of Bladed Discs-Some Experimental Observations," by J. C. McBain, AFWAL

Session V

2:00 to 4:00 P.M.	Aeroelastic Instrumentation Research Chaired by L. J. Kiraly, NASA/LeRC

33 "Dynamic Flow and Pressure Sensors for Aeroelasticity Experiments," by D. R. Englund and L. N. Krause, NASA/LeRC

34 "A Simple Fixed-Probe Technique for Periodically Unsteady Flows," by R. P. Shreeve, Naval Postgraduate School

35 "Optical Measurement of Blade Flutter," by W. C. Nieberding and J. L. Pollack, NASA/LeRC

36 "Non-Interference Measurements of Compressor Blade Stress," by P. McCarty, ARO, Inc., AEDC Division

37 "Blade Vibration Data Acquisition System," by J. Frarey, Shaker Research Corporation

38 "High Speed Random Decrement Algorithm," by L. J. Kiraly, NASA/LeRC

4:00 to 4:30 P.M.	NASA Flutter Compendium AGARD Aeroelasticity Compendium
4:30 to 5:30 P.M.	Assessment/Remaining Issues - Flutter

October 29, 1980

Session VI

8:00 to 12:40 P.M.	Unsteady Aerodynamics - Forced Vibration (Anal./Exp.) Cochaired by J. J. Adamczyk and C. L. Ball, NASA/LeRC

39 "Three-Dimensional Periodic Disturbances Acting Upon Airfoils in Cascade," by H. Atassi, University of Notre Dame

40 "Wake Cascade Interactions," by G. W. Englert, NASA/LeRC

41 "Wake Induced Vibration of Axial Components," by J. Caruthers, University of Tennessee Space Institute

- Unsteady Aerodynamics - Forced Vibration (Anal./Exp.) (cont'd)

42 "Unsteady Aerodynamics in Transonic Cascades," by M. H. Williams and E. H. Dowell, Princeton University

43 "Inlet Flow Distortion in Turbomachinery," by B. S. Seidel, University of Delaware

44 "Fluctuating Air Loads Due to Large Length Scale Inlet Flow Distortions," by G. Linn, NASA/LeRC

45 "Vortex Whistle-An Unsteady Phenomenon in Swirling Flow in Turbomachinery and Its Implication," by M. Kurosaka, University of Tennessee Space Institute

46 "Strut Induced Aerodynamic Forcing Functions in Axial Compressors," by B. C. Clem and E. Greitzer, Massachusetts Institute of Technology

47 "Aerodynamically Forced Vibration of Radial Flow Components," by J. E. Caruthers and M. Kurosaka, University of Tennessee Space Institute

48 "Periodically Unsteady Flow in an Imbedded Stage of a Multistage Axial-Flow Turbomachine," by T. H. Okiishi, Iowa State University

49 "Time Varient Aerodynamic Response of a Stator Vane Due to Wake Induced Gusts," by R. L. Jay and W. A. Bennett, Detroit Diesel Allison, Division of General Motors Corporation

50 "Unsteady Stalling Reponse in an Axial-Flow Compressor with Applications," by W. F. O'Brien, Virginia Polytechnic Institute and State University

51 "Time-Varient Aerodynamics for Torsional Motion of Large Turning Airfoils," by R. L. Jay, Detroit Diesel Allison, Division of General Motors Corporation

- Unsteady Aerodynamics - Forced Vibration (Anal./Exp.) (cont'd)

52 "Forced Fan Blade Vibration Caused by Various VTOL Inlets Operating at High Angles of Attack," by R. C. Williams, NASA/LeRC

Session VII

1:40 to 2:40 P.M. Structural Dynamics-Forced Vibration (Anal./Exp.)
Chaired by R. Kielb, NASA/LeRC

53 "Recent Investigations of the Forced Vibrations of Multiple Blade Systems with Slip and Mistuning," by D.I.G. Jones, AFWAL and Agnieszka Muszynska, Visiting Scientist, University of Dayton Research Institute

54 "Vibration Analysis of Turbine Engine Blades," by A. Leissa, Ohio State University

55 "The Influence of Gyroscopic Forces on the Dynamic Behavior and Flutter of Rotating Blades," by F. Sisto, Stevans Institute of Technology

2:20 to 3:30 P.M. Assessment and Recommendations-Forced Vibrations

A History of Aeroelasticity in Gas Turbine Engines in the United States & United Kingdom

Disclaimer. The subject of this paper may be approached by an inclusive chronological summarization of the various nonsteady aerodynamic analyses, with the consideration of more and more governing parameters or physical effects of importance. This procedure has been very effectively pursued by Professor Max Platzer in a series of recent papers. The result has been an awareness by the turbomachine aeroelasticity community of the status at any time (and the evolutionary development) of the field primarily from the aerodynamics side.

A similar summarization from the structural side has not been presented, probably stemming from similarity of the structural dynamics problems in other fields of application. Owing to this relative lack of coverage, the present historical summary will dwell more heavily than might otherwise be appropriate, on dynamical aspects of the structure.

Overriding this question of aerodynamic/structure balance, however, is the attempt overall to provide literally a historical flavor to the subject matter. Thus, for example, there will be a concern with relating developments in the aeroelasticity of gas turbine engines to the level of research effort extant at the time, the general status of aeronautics, air-breathing propulsion, and so on.

There will be no review of Soviet Union experience in this historical summary.

Antecedent Period. Aeroelasticity as an empirical field of engineering stretches back into recorded history with accounts of flutter occurences in the early "iron" suspension bridges in England (1818). The vibration of tall smokestacks and other bluff structures by Karman vortex excitation are other examples all of which persist to the present day (cf. Tacoma Narrows Bridge failure in 1940) as important phenomena of fluid-structure interaction*. Airplane empennage and wing flutter became a

*The failure of Langley's Aerodrome (1903) while attempting to operate from the houseboat on the Potomac was probably due to wing divergence and is an example of static aeroelasticity which is not considered in this treatment of gas turbine engines.

recognizable problem around the time of the WWI and analytical treatment became possible with the nonsteady aerodynamic theories of Birnbaum, Wagner, Glauert, Theodorsen (1934) and others in subsequent years. Stalling flutter of lifting surfaces was investigated experimentally somewhat later by Studer (1936), Bratt el al (1940), Mary Victory (1943) and others.

Gas Turbine Engines. The emergence of the first really successful gas turbine engines were essentially the turbojet powerplants developed in England at the end of and immediately after WWII. This development coincided almost precisely with the first important documentation of axial compressor blade flutter as reported retrospectively by Shannon (1946). The critical values of reduced frequency $\omega b/V = 0.2$ in bending and $= 0.75$ in torsion indicate that for the somewhat lower aspect ratios and greater blade thickness of the times, stalling flutter in bending was a distinct possibility and an observed occurrence. And this continued to be true into the mid 1950s. However, torsional stalling flutter became steadily more prevalent as the decade wore on, probably related to changing blade geometry (higher AR, smaller thickness, maximum thickness further aft chordwise) and higher relative velocity as compressor Mach numbers increased. The gross features of stalling flutter were explained by Sisto (1952) using a nonlinear model of dynamic stall behavior.

The First Flowering. The decade of the 1950s saw a great deal of activity in axial compressor aeroelasticity, much of it of a confusing or apparently contradictory nature. Perhaps this was to be expected in a burgeoning field of accelerating growth.

As the period opened the true supersonic compressor was being intensively developed by the then NACA and others. Almost as compromise fallout of this effort the transonic compressor began its development toward the end of the decade. The extremely robust blade profiles of the all-supersonic compressor gave way to airfoils even more susceptible than the earlier subsonic designs of the Whittle-Howell-Carter era. With thin, tapered, twisted airfoils of higher aspect ratio and lower hub/tip ratios the possibilities for flutter and vibration increased significantly.

At about the same time the phenomenon of propagating stall was discovered and researched by groups at NACA (1953), Cal Tech (1954) and Harvard/MIT (1954). A strong controversy arose concerning the relative significance for blade vibration of propagating stall *vis a vis* stalling flutter. At one time there was serious question whether separate mechanisms were involved and whether in fact there was such a distinct phenomenon as stall flutter. The controversy continued to find expression well into the following decade, but general agreement now separates the two types of stall-provoked vibrations by noting that propagating stall results in forced vibrations much as any other asymmetric flow in the blade annulus. The vibration of the annularly cascaded blades exerts little or no influence on the propagating speed of the stall and hence on the forcing frequency. Stalling flutter on the otherhand, is a true self-excited vibration as is conventionally implied by the term "flutter".

With the stall propagation/flutter controversy eventually resolved, the 1950s saw also the appearance and widespread use of part-span shrouds to control the vibrations of higher Mach number compressor blades and the fan components of the nascent turbofan engines. Some controversy exists even today as to the reason(s) for effectiveness of these "bumpers". There is an unquestioned stiffening effect on the structure thus providing an increased dimensionless frequency and modification of the vibration mode, both aeroelastically important. However, during vibration it is also true that the interfacial surfaces between butting shrouds elements may introduce mechanical damping. It is probable that both benefits accrue and that one effect or the other may be optimized by the particular philosophy employed in their structural design. It is interesting to observe that the turbine component has made use of tip shrouds as a viable option from the earliest gas turbine engine development, probably as a naturally carry-over from earlier steam turbine practice.

In this same time period the significant use of variable guide vanes in compressor components was observed after an intensive R & D period. The research on aeroelastic implications of these devices was largely experimental and improved stalling-flutter avoidance was one of the major results.

In this first flowering of gas turbine aeroelasticity of the 1950s one of the most fascinating anomalies was the widespread analytical research devoted to the so-called "classical" cascade flutter. Considering the basic model of a two-dimensional cascade of flat plates at zero incidence, intensive analyses were initiated by Billington (1949), Lilley (1952), Sisto (1952) and others. These aerodynamic considerations continued up to the present day with greater accuracy and treating more and more geometric parameters of interest and thus embellishing the basic model accordingly (e.g. thickness, camber, nonzero incidence).

The anomaly of this vigorous and widespread series of investigations was the common knowledge, early on, that this type of flow (unstalled) did not lead to flutter in axial compressors of practical structure! Nevertheless the analytical wheels kept grinding and improving. Finally, when flow compressibility was added to list (Lane 1958) analytical prospectors of aeroelastic gold began to hit pay dirt! Supersonic flutter was to become of transcendent interest in the 1970s.

The Dark Ages. Although some gas turbine aeroelastic research continued in the 1960s, it was a relatively quiescent period, particularly at the beginning of the decade. This was attributable in some measure to Sputnik, the subsequent American response and the consequent beginning of the Space Age. NACA was converted to NASA and effectively devoted most of its effort to space programs to the relative exclusion of airbreathing engine research.

Aeroelastic research during this period was conducted mainly in industry laboratories and was highly proprietary and developmental in nature. It was not until the end of the decade that compressibility in the supersonic regime began to be researched analytically.

This was the period in which transonic fans continued their development with the widespread use of Titanium alloy and its beneficial strength/weight ratio. This aeroelastically superior front stage material helped sustain new engine development without the need for corresponding intensive aeroelastic research in support of those developments. However, even the advent of Titanium did not prevent the appearance of an additional row (i.e. two rows) of part span shrouds in a fan blade row and the serious consideration of 3 rows.

The entire lift engine development, in all its variants, peaked out during the Dark Ages. Many interesting composite blade materials and types of construction were tried; the aeroelastic benefits in the area of flutter performance were apparently insufficient to overcome the aeroelastic disadvantages of FOD and fatigue behavior in forced vibration. Although these lift engine developments have now been largely abandoned (with the vectored-lift Pegasus an exception which continues in tactical service), a great deal was learned about the aeroelastic features of resisting FOD, other transient loadings and the special inlet distortions encountered with lift engines.

Although the aeroelastic consequences of operating in distorted flow were recognized from the beginning (late 1940s) probably as a consequence of earlier experience with partial admission steam turbines, the serious study of aero-mechanical response to flow distortion took hold late in the decade (Armstrong, 1966). This seemed to be due in some measure to the increased use of buried engine installations requiring bifurcated and/or tortuous inlet ducting, supersonic inlets operating off-design and a trend toward lower cantilever blade frequencies. Stemming from the limitations to, and deterioration of, engine performance in distorted flow, the serious research of this subject had a positive stimulus in extending the studies into the area of aero-mechanical response as well.

Finally, the 1960s were notable for establishing the public annoyance with noise levels in the vicinity of airports and the acoustic anguish anticipated when the SST would begin commercial operation. That the acoustic approximation can be effectively employed in analyzing unsteady flow through cascades and that virtually the same theory predicts the characteristics of acoustic radiation from such a device provides an interesting perspective as calendar time advanced from the sixties to the seventies.

Renaissance. The emergence from the period of reduced aeroelastic progress, termed here the Dark Ages, was gradual but well underway by 1970. Increased research support was gathered for all aspects of aeroelastic science and technology in the aeroengine field. The greatest proportion of this support, however, has been for the identification and treatment of high subsonic* and supersonic flutter and the firm establishment of the related field of aeroacoustics. Analytical capability and experimental verification in this important area has expanded tremendously and continue to receive well-merited attention.

At the same time the engine characteristics in which these pheonomena are important have evolved in such a manner that it is now essential to treat the vibrating structure as more than a typical cantilever blade. The discovery of the bladed disk assembly as the relevent structural system to be considered has borne fruit and the concept has been expanded and refined for inclusion in modern flutter and vibration analyses. Experimental data have confirmed the existence of forward and backward travelling waves in these shrouded-bladed-discs with various numbers of diametral (and zero, one or two circular) nodal lines. Technology is growing rapidly and the concept of "aeroelastic modes", having both structural implications as noted above, and aerodynamic implications as would be required by more than one value of interblade phase angle existing simultaneously is being vigorously developed. Mistuned blading systems are being given increased attention.

This situation is quite new and exciting since in the past the concept of aeroelastic modes was not required to explain and predict flutter. The more robust structure and relatively incompressible flow allowed an accurate treatment with only the

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*Choking flutter is another phenomenon in which compressibility plays a key role.

natural coupled modes of the structure being known.

These more sophisticated structural description are finding use as well for the modern description of distortion response since the excitation field by definition rotates relative to the excited blade row. It is interesting to note that many of these modal concepts of bladed disc assemblies have their roots in the work of Campbell (1920s) and others in the steam turbine field.

Further complications in modern bladed-disk geometries and their structural characteristics are provided by the aircraft in which the aeroengines are mounted. These relatively flexible rotating structures may be subjected to variety of precessional histories. The gyroscopic reactions become important and research is required to understand and predict the consequent phenomena.

Experimental aeroelasticity has benefited greatly from modern developments in transducer developments, telemetry and the use of microprocessors in data acquisition and processing. Confirmation of the more sophisticated aspects of modern theory by experimental means is now increasingly feasible.

Another encouraging development related to the modern high speed digital computer is the increased capability to study fairly complex systems of interacting vortical elements in unsteady flow. Large storage and short computing time have increased the feasibility of tracking such flows which are essential to modern stall flutter models and their quantitative study. It is possible that stall flutter may legitimately enter a phase of theoretical (i.e. non-empirical investigation.)

Finally, the increasing attention to nonlinearities is a hallmark of the renaissance in turbomachine aeroelasticity. Nonlinearities in the aerodynamic formulations which are receiving attention are due to shocks, large deflection passages, vorticity transport and the like. In the structural description the nonlinearities are related to large deflection theory, in the main, although time dependent stiffness and damping coefficients (or matrices) are becoming important and being studied. The latter are not strictly nonlinear.

Epilogue. This historical recitation has attempted to lay the groundwork for understanding the present state of the art in respect of aeroengine aeroelasticity. The account has not been exhaustive nor, hopefully exhausting to the reader. Rather some salient features have been placed chronologically in order, providing a bridge from the past up to the present. A recitation of all current and proposed new lines of effort has not been attempted since this is the subject of our present Symposium. No doubt some important developments have been slightest, or not recounted at all. It will be found, however, that each of these new areas of aeroelastic endeavor has its roots in what has been recounted here.

APPENDIX C

PROPULSION TRENDS OF AEROELASTIC INTEREST

Banquet Talk

Symposium on Aeroelasticity of Turbine Engines

Lewis Research Center
NASA

October 27, 1980

I am very happy to be here and to see so many here tonight considering the title of my talk, You are the truly dedicated.

I say that because I feel that the title for this talk is stuffy and a little presumptious. In fact, it is presumptious on two counts. First, it presumes that I know what the trends in propulsion actually are. (And announces that I have the gall to say so at a place like Lewis!) And second, it presumes that I know which of these trends will be of interest to a widely recognized and distinguished group of aeroelastic experts. Namely, you.

By way of explanation and apology, I submit that there are special social dynamics which surround the selection of a title for a talk, and that these circumstances give the title a life of its own. The invitation to speak, of course, initiates this set of social dynamics. At least in my case, the speaker was pleased and honored to be asked to speak! (I think anyone would have been.) Shortly after such a kind invitation is offered and accepted, there follows a series of phone calls back and forth regarding the need for visual aids, about how long the talk should run, requests for biographical material and details with which you all are either familiar, or can imagine, and to which the speaker attempts to respond expeditiously. Then comes the request for the title. The need is usually urgent, because of the long lead-time needed to prepare announcements, to get them run off, and allowing for distribution through the U. S. Postal Service. Inevitably the urgent request for a title reaches you while you are on a trip, and the creative time for coming up with a title is somewhere between the shower (in your motel) and the second cup of coffee at breakfast. Once the phone call has been made, transmitting the fruits of your deliberations (in Howard Johnson's, a Holiday Inn or a Best Western, by dawn's early light) you are committed. At that point the newborn title begins to exert its influence. The talk is then prepared under constraints which your creativity or lack of it has erected for you. Either that, or you have to be the kind of strong character that can stand up and say "never mind the announced title, here's what I'm going to talk about tonight."

Nevertheless, and all of the aforesaid notwithstanding, I do intend to try to speak of trends in propulsion development tonight, and how these new developments could conceivably call for new, different, or re-emphasized aeroelastic analysis, design and testing.

Now I should say, before someone says it for me, that I am certainly not a propulsion expert. In fact, my particular vantage point is probably best described as that of a semi-informed outsider, looking in. My window for this "looking in" is the NASA and Air Force advisory apparatus. And the view that I get is an exciting and a challenging one. Propulsion continues to be, as it has been virtually from the outset of aerospace endeavors, a crucial discipline. Without it manned flight is restricted to what can be accomplished within the limits of geography -- i.e. in choosing high cliffs from which unpowered flights can be launched -- and meteorology i.e. the availability of thermals to sustain unpowered flight. With superior propulsion, aircraft of all kinds have a major competitive advantage, whether the competition is in the marketplace or over the battlefield.

I'll speak of trends in two general areas. The first, new applications or propulsion hardware developments which appear to be leading to substantially different configurations. And second, developments which are driven by environmental or operational considerations unlikely to result in major configurational changes, but whose impact is likely to be substantial.

The first area that comes to mind is airframe-engine integration. Objectives in this aspect of propulsion system design for military applications, are almost diametrically opposed to those for commercial applications. In commercial applications, fuel economy, reliability, low noise and vibration in the cabin and noise externally, ease of access, for maintenance and protection of passengers and airframe in the event of an engine - associated structural failure are all essential considerations. They lead to engines which are mounted, first, generally clear of the aerodynamic influences of the airframe, second, as far from the passenger compartment as stability and control considerations including engine-out performance will allow, and third, where maintenance crews can get at them easily. This tends to have rotating engine components, (such as axial compressor and fan sections) operating in relatively uniform axial flows. On the other hand engines on commercial aircraft tend to be mounted on rather flexible structure. Thus, aerodynamic forcing functions resulting from inlet flow distortion will tend to be milder, but the elasto-dynamic coupling between fixed and rotating parts, (as for example in determining shaft whirl speeds and the vibratory environment in which engine parts and accessories must operate) are matters which cannot be dealt with by considering either the engine or the airframe or both in isolation.

We all know there is nothing new under the sun and this general problem has always been with us. However, larger engines with lighter and lighter structures, and attempts to simplify component designs (such as eliminating shrouds on fan blades) all tend to make these problems more critical.

In the military area, the emphasis is on maximum performance, on protecting the engine from enemy fire and on minimizing the engine's output of signals which increase the likelihood of the aircraft being detected; signals such as IR and radar reflections. These factors tend toward buried engine installations. As a result, incoming flows tend to be more distorted and rotating fan and compressor components are therefore subject to more severe aerodynamic forcing functions. While this is true for all combat aircraft, including bombers, these situations will be aggravated for fighter aircraft in which engine inlet angles of attack may reach unusually high values in combat maneuvers.

In short, efforts to more effectively integrate airframes and engines will be on the increase in the years ahead. Many of these integration problems are purely aerodynamic, such as the effect of aft-fuselage-mounted nozzles on "base drag". But I've tried to focus on those with aeroelastic ramifications.

A second area of growing importance is the development of new propellers. The advanced turboprop program being conducted by the Lewis Research Center has some extremely important goals for the nation. It is estimated that domestic commercial air carriers require roughly 10 billion gallons of fuel a year. At approximately $1 dollar a gallon, every 1% improvement in aircraft fuel consumption by commercial air carriers, therefore, means $100 million dollars saved each year. Not to mention the effect of these savings on the balance of payments to sources of foreign oil in such unstable regions overseas as the Middle East.

The advanced turboprop program has the objective of making practical turboprop aircraft capable of cruising at Mach numbers of about .8 and at altitudes of 30,000 ft or higher. Very promising efficiencies at realistic operating conditions have been achieved with advanced turboprop models in wind tunnel tests at reduced scale. These improvements indicate that 20% fuel savings could be achieved over turbofans using the same engine core technology. If these advanced turboprops using an advanced turbine engine core are compared with current turbofan engine technology, then the possible improvement is 30%. It's clear that converting the entire commercial fleet to advanced turboprops could save somewhere between 2 billion and 3 billion dollars (and gallons of fuel) a year even at current prices.

So much for the incentive; now about the aeroelasticity! The advanced turboprop being developed by Hamilton Standard doesn't look much like a conventional aircraft propeller. First of all, the latest version has 10 blades. Next, they are of smaller diameter than conventional propellers and have variable sweep. The blade shape is roughly like a scimitar. The aeroelastic implications of such a configuration certainly seem clear. Not only are flutter and other forms of instability a consideration, but the excitation to be experienced operating in the aerodynamic flow field near swept wings or in proximity to the fuselage or tail will cause substantial dynamic response. Such effects cannot safely be ignored either in predicting the structural integrity and useful lifetime of such blades, nor in determining the vibration levels and noise levels generated and experienced inside the passenger compartment and -- so far as noise is concerned -- on the ground, as well.

A second area of new propeller developments is in General Aviation. As things stand now, European propellers, ROTOL's particularly, are flying on and being ordered for large numbers of U. S. General Aviation aircraft. This is affecting the U. S. propeller industry seriously. For those who haven't considered the state of the General Aviation industry in the U. S. lately, I will take a moment to mention a few statistics.

In 1978 the U. S. General Aviation industry had 2.8 billion dollars in sales. This was approximately 42% as large as the impressive figure for commercial transport aircraft built in the U. S. in that year. Even in

1979, when commercial transport aircraft sales in the United States almost doubled to 8.1 billion dollars, General Aviation grew significantly too, so that it fell to only a little less than 30% of the commercial transport figure. Perhaps more important statistics for equipment such as propellers include the facts that about 5,000 commercial air transports have been built, the total of all 707, DC-8, 880, 990, DC-9, 727 & 737 production, for service anywhere in the world. That kind of production for a new generation of transports is not expected to grow a great deal as larger transports continue to replace smaller ones. On the other hand, there are about 200,000 General Aviation aircraft now operating in the U. S. alone. And that number is expected to grow to over 300,000 by 1990. Getting back into the General Aviation propeller business (with real strength) will take major innovations probably in configurations, materials and fabrication technology. As design margins are pushed to achieve competitive advantage, aeroelastic considerations will grow in importance.

Similarly, turbine engines for General Aviation aircraft is a subject of growing importance. All those statistics which argue that it's a good idea to make sure that the U. S. propeller industry is competitive in the General Aviation area hold also for turbine engines for General Aviation aircraft. The criteria for General Aviation engines are (as you might imagine) different than for commercial transport engines. General Aviation flights are shorter, take-offs and landings per flight hour considerably more numerous. Exposure to ground damage and higher numbers of cycles of the kind which cause low-cycle fatigue are much greater per flight hour. Furthermore, initial price is a more important factor, since the operators of General Aviation aircraft (even including commuter transports) are less capable of major capital expenditures. Here again, it is easy to overlook the importance of the General Aviation field. I was surprised to learn recently from NASA Headquarters that fully 1/3 of the air passengers carried into United States cities are passengers on General Aviation aircraft. Four typical General Aviation aircraft have seat-mile/gal. performance ranging from 75 to 90; that's like a two-passenger car with 45 mpg on the highway! We can hardly afford, as a nation, to ignore turbine engines for the next generation of these aircraft, which includes Commuter Transports.

Still another area of new aircraft engine development is provided by attempts to evolve a practical VSTOL aircraft. Here one of the most exciting concepts for VSTOL engine systems is the so-called "four-poster". The "four-poster" gets its name from the way it is put in equilibrium in the vertical take-off and landing mode. Four columns of air both support the aircraft, and provide control. The four columns are supplied by 2 nacelles, symmetrically disposed, one on either wing. The rear-most column of air (on either side) is provided by the usual jet efflux of a turbine engine, turned through 90^{o} and augmented by either over-the-wing or under-the-wing blown flap systems. The forward column of air on either side is provided by a high by-pass fan whose output is turned 90% by a cascade of vanes within the engine duct. It is proposed to provide equilibrium and all control moments by modulating the magnitude of the thrust and/or its direction in each of these four columns of air, -- for the aft columns by cycling the flap systems; for the forward column by cycling the vanes in the cascade. Thus, in the "four-poster" VSTOL configuration, all V/STOL thrust and control is contained in only two nacelles. Conceivably the remainder of the airframe could be quite conventional. Although the "four-poster" nacelles would presumably be rather large, the need for auxiliary rotors or reaction jets at the wing tips or nose and tail becomes unnecessary. Should this concept succeed, it seems fairly obvious that the effect of a cascade of vanes oscillating (to provide control) on the fan section rotating just ahead of these vanes will involve forced-response aeroelastic problems of the first order.

Moving to helicopters as another aircraft type in the VTOL category, a whole series of special turbine engine developments is likely to emerge. Regenerative cycles are being considered as well as compound engine cycles. The latter would allow taking all power through the shaft in the hover mode but provide for partial-power take-off through a by-pass fan or propeller in the forward flight mode. These arrangements have great attractiveness for high-speed rotorcraft. More conventional transmission problems of rotorcraft should not be overlooked either. In developing very large helicopters compared to what we have today we have only recently encountered helicopter gear box systems where the elasticity of the gear rings which hold the gear teeth are a significant factor, not only in gear wear but in structural dynamics of the transmission system. The coupling between drive system and engine in a helicopter has been an airframe-engine integration problem from the very beginning, of course, and these aspects promise to be increasingly important as larger and lighter and more flexible drive systems are developed.

Mentioning variable cycle engines for helicopters brings me to the last on my list of new engine developments with significant configurational changes. This is the so-called "VCE", or variable cycle (turbojet or turbofan) engine. The variable part here is variable by-pass ratio. The importance of variable by-pass for the commercial engine is that it would provide both high static thrust with low external noise levels for take-off and landing conditions, (for such is associated with high by-pass) and yet it would be capable of the higher thrust levels (for supersonic flight) associated with a pure (no by-pass) jet engine. Having such an engine could alleviate substantially the financial difficulties the Concorde experiences in today's environment. VCE developments are being pursued in the United States at a deliberate pace, both anticipating the day when a commercial supersonic transport may be economically viable and also because a VCE capability is important for bombers and for short take-off and landing fighters. For both of these military aircraft categories high static thrust, efficient subsonic cruise and supersonic dash capabilities may become essential performance combinations. The mechanical means by which the variable by-pass ratios will be achieved, of course, will involve moveable doors within the by-pass flow ducts. These doors will (in one position) allow the by-pass flows and in other positions will restrict or not allow them. It goes without saying that the rigidity of these moveable doors will be one of the important design criteria for the engine. Any substantial plate or shell vibrations of these doors (or their motion as a rigid body) are likely to feed back up-stream to the fans and become an intolerable source of excitation for the rotating components. Closed loop feedback seems a possibility.

Now let me turn to emerging, new operational considerations that probably will impact both engine designs in the future and in the amount of aeroelastic analysis and testing that will have to be done to make these engines operate successfully. First, there are three developments underway which will influence the materials used in new engines. The first of these is NASA's technology program to improve the life of the hot section components of advanced turbine engines ... the so-called HOST program. As a result of the emphasis of recent years, the technology for improving the performance of advanced turbine engines has outpaced the technology for achieving long part-life for hot engine section components. The current high performance/high by-pass ratio engines have relatively poor durability in their hot section components. The NASA program intends to improve combustor liner and gas-path seal life, and I believe it will succeed. In addition, however, the turbine blades and other parts in the hot section will use different materials and/or configurations with the objective of improving part life, but these changes will almost certainly have the side-effect of changing aeroelastic properties.

The second of the major programs which is likely to lead to new engine materials and perhaps configurations responds to the need to adapt present day engines to operate successfully on fuels which are alternative to present-day aircraft fuels. While aircraft use substantial amounts of fuel in absolute terms (as I mentioned earlier in alluding to the need for fuel efficiency programs) the total of all aviation fuel consumption in the United States is only 4% of the total of petroleum-based fuels used in our country. It would, therefore, be imprudent to assume that (as the need for alternative fuels grows) the petro-chemical industries will be driven by the needs of one of the smallest users. Aviation may be forced to use fuels with properties that are dictated by other users (i.e. the other 96%). Thus aircraft engines are likely to have to be capable of using fuels which have a broader range or at least different properties than current aircraft fuels have. While I cannot anticipate what changes in engine configuration will be required to meet this need, it is an area where aeroelasticians will have to be alert to possible effects on engine dynamics.

The third of the areas which may result in the use of materials in turbine engines with new and different properties is defined by the urgent need to replace the strategic materials currently used in engine structural parts. Several elements which are important constituents of the so-called super alloys used in gas turbine engines are strategically critical because of our almost total dependence on imports subject to political and economic uncertainties.

Principle among these materials are cobalt, chromium and tantalum. Cobalt and chromium are available to us (in any substantial quantities) only through African nations. And tantalum is unique among these elements not only because we are totally dependent on foreign sources such as Thailand, but because the known reserves are limited in an absolute sense. Not only has the availability of tantalum become marginal recently, but the price has tripled in one year, (i.e. from '79 to '80). Strong efforts to understand the role of these elements in metallurgical technology, and to replace them will, I believe, be undertaken. The extent to which they succeed will determine another source of change in the mechanical properties of engine components which must be dealt with by the aeroelastician.

The final operational aspect which I think will affect new engine design springs from a management program; namely, the United States Air Force's program which has the acronym ENSIP. This stands for Engine Structural Improvement Program. ENSIP has the goals of increasing engine structural safety and service readiness, and reducing life-cycle costs. It intends to accomplish these goals by substantially reducing the occurrence of structural durability problems in service operations. In a detailed study, the Air Force found that structural problems on engines have resulted in inadequate engine durability and in some cases inadequate safety. There have been, for example, many engine failures of the TF-41 turbine on the A-7 aircraft and many such aircraft have been lost becuase of such engine failures, with high impact on operational efficiency and cost. Several F-111 aircraft have been lost because of failures of their TF30 engine. In the last year alone, three F-16 fighters have been lost due to engine failures in its F-100 engine. Such failures have taken place in blade, disc and vane components. They have not been restricted to fighters, but have been encountered in the TF-34 engines used in the A-10 attack aircraft and in the TF33 engines used in the C141 military transport, as well. (Although aircraft haven't been lost due to those engine failures.)

The need for an ENSIP program was justified by the Air Force Scientific Advisory Board as long ago as 1976, but the impact of this program is only just being felt. Detailed assessments of the structural durability of specific engines conducted under ENSIP have led to the conclusions that engine frame cases, blades, discs and bearings, vanes and thin-shell structures failed in fatigue caused by high frequency oscillations driven by aerodynamic, sonic or mechanical vibratory excitation, and that in most cases the problems could have been avoided, had complete and timely design analyses, tests and force management procedures been employed. An important part of the ENSIP program is to identify early in an engine development the vibratory environments to be encountered, and to predict stresses analytically and verify them by test. Thus, ground vibration, strain and flutter surveys; external component resonance searches; installed engine vibration and stress surveys and unbalanced rotor vibration and stress surveys are called for as necessary steps in defining the engine's operating environment.

As the lessons that the Air Force has learned in the ENSIP program are applied, new requirements for realistic structural analyses and tests will be imposed, to an extent which is beyond that existing heretofore, to confirm component life for Air Force engines. I believe the role of the aeroelastician in these more comprehensive and detailed analyses and tests will be substantial.

Some of the new propulsion applications and hardware developments and some of the new operational and environmental factors which will change aircraft turbine engine design that I've spoken about may seem relatively routine and evolutionary. Some may seem revolutionary and far-out. I am sure I haven't touched on all such changes which will influence the kind of work we will be doing in the next five, ten or fifteen years. Neither am I sure of being successful in putting my finger on the most important of those changes that will take place. All I am sure of is that such changes as those I have mentioned will, in fact, occur and that we must be prepared to deal with them.

In closing, I would like to leave you with a few quotations intended to ensure that you will not be thinking too conservatively or pessimistically as you look to the years ahead. Bill Walls of Boeing-Vertol recently cited the following during the recent Woods Hole study of NASA's role in aeronautics:

> Lord Kelvin, the eminent 19th century physicist who postulated the 2nd law of thermodynamics is quoted as saying "X-rays will prove to be a hoax."; "Radio has no future."; "Aircraft flight is impossible."
>
> Henry Ellsworth, the United States commissioner of patents said, in 1844, "The advancement of the arts of invention from year to year seems to presage the arrival of that period when further improvement must end."
>
> Octave Chanute, an aviation pioneer, said in 1904 "The flying machines will eventually be fast. They will be used in sport, but they are not to be thought of as commercial carriers."
>
> Even Wilbur Wright, in talking about the possibility of helicopters, said "The helicopter does with great labor only what the balloon does without labor and is no more fitted than the balloon for rapid horizontal flight. If its engines stop, it must fall with deathly violence for it can neither float like a balloon nor glide like an airplane. The helicopter is much easier to design than the airplane, but it is worthless when done."

And finally, quoting Arthur C. Clark, "When a distinguished but elderly scientist states that something is possible, it is almost certainly right. When he states that something is impossible, he is very probably wrong."

I conclude from all this that very exciting and challenging propulsion developments and refinements are ahead of us, and that as in all other fields, the more refined developments become, the more likely is the exposure to aeroelastic phenomena. We all will have our work cut out for us to see that in the future as in the past the aeroelastic tiger in the bushes will continue to be kept at a safe distance.

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A summarization in overview format of the joint NASA/AF/NAVY Symposium on Aeroelasticity of Turbine Engines held at NASA-Lewis Laboratory on October 27, 28 & 29, 1980. Fifty-five presentations were made in Unsteady Aerodynamics and Structural Dynamics, including self-excited (Flutter) instability and structural dynamics. Both analytical and experimental work was reported. A brief history of the subject and the text of banquet talk are included.

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